Implications of As-built Highway Horizontal Curves on Vehicle Dynamic/Kinematic Characteristics Under Adaptive Cruise Control

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Abstract

Due to the presence of the road’s curvature and sensors’ limited field of view, as-built highway curves designed based on traditional human-driven vehicles’ characteristics pose a challenge to the adaptive cruise control (ACC) system and its shared control. However, very few efforts in the literature were expended on exploring the adaptability of the ACC system-dedicated vehicle (V-ACC) from the perspective of vehicle-road geometry interaction. Therefore, the objectives of this study are threefold: (i) to investigate the implications of existing horizontal curves on V-ACC dynamic and kinematic characteristics; (ii) to unravel the impact mechanism of curve geometric features; and (iii) to evaluate the ACC system’s adaptability from different aspects and extract the critical curve geometric features. To this end, a virtual co-simulation platform was established and validated by the OpenACC database. A series of tests featuring circular curve radius ($R_C$), desired speed ($V_{de}$), and desired clearance were created, and V-ACC characteristics were output. The results show that: (i) a smaller $R_C$ causes V-ACC characteristics toward the margins of safety, comfort, and speed consistency, but neither sideslip nor rollover occurs, and speed consistency is good; (ii) the driver and passengers (if any) feel comfortable at $V_{de} = 40, 80-100$ km/h following the leading car, but they may feel moderately uncomfortable at $V_{de} = 50-70$ km/h when $R_C$ decreases toward its lower limit; and (iii) asymmetrical maneuvers and discomfort would exist before and after the circular curve. These findings could help road administrators regulate V-ACC’s behaviors and improve its road-oriented operation design domain.
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Index Terms—Adaptive cruise control, driving comfort, highway geometry, vehicle dynamics and kinematics, virtual simulation.

I. INTRODUCTION

Technologies of advanced driver assistance systems (ADAS, Levels 1 and 2) will evolve up to full driving automation (Level 5) classified by the International Society of Automotive Engineers [1]. However, such complete automation will not be developed overnight, and different automation levels will coexist on the roads [2]. Moreover, numerous physical road infrastructures have been built, and most of them, especially their road geometry, were designed only considering the characteristics of human drivers or traditional human-driven vehicles (HV) [3]. Therefore, a considerable timeframe is needed to examine the adaptability of various automation features to the as-built physical road infrastructures. Note that the ‘adaptability’ here refers to safety, feasibility, and driver/passenger-oriented comfort [3,4].

The adaptive cruise control (ACC) system (Level 1), a significant feature of ADAS, has been deployed in an increasing proportion of commercial automobiles [5]. Given the anticipated performance on accurate detection and robust car-following control, the transport research community has seen it as one of the most inspiring automation technologies [6]. Also, the ACC system, which automatically executes the sustained longitudinal vehicle motion control for improving comfort, can still be integrated and activated by future automated vehicles (AV) [1]. Note that commercial driving automation features are still in their infancy, i.e., they have yet to mature from ADAS to Automated Driving Systems or connected automation due to such limitations as technology, cybersecurity, and standardization [7]. In addition, human drivers tend to use longitudinal or lateral automation functions (e.g., ACC system or lane-keeping assist system, respectively) separately even though they can be engaged together (i.e., Level 2) due to distrust and inexperience [8,9]. In these regards, we focused on the ACC system-dedicated vehicle (V-ACC) in which the human driver controls all vehicle lateral motion.

Specifically, V-ACC first uses sensors to detect and track the leading car for measuring the inter-vehicle distance and speed differences. Then, it controls the acceleration or braking systems to maintain the desired clearance or speed [2]. Meanwhile, the human driver monitors the road-traffic scenario ahead and maneuvers the steering wheel to negotiate the system’s longitudinal maneuver. Given different control sequences between V-ACC and HV, many efforts regarding ACC systems in the literature were paid to mapping their features through various modeling approaches (e.g., mathematical models [5]. Based on that, numerical or virtual simulation methods are further used to analyze the impact of ACC systems on traffic flow characteristics (e.g., stability [10]) or traffic-related features (e.g., response time [2]). In addition, some previous studies [11] collected naturalistic or empirical data to observe such an impact directly, and they [12] attempted to capture the ACC-related factors (e.g., time gap...
setting, acceleration/deceleration constraints) influencing traffic safety, stability, or efficiency. They also captured the traffic-related features (e.g., penetration of V-ACC) influencing V-ACC’s driving performance on the contrary [13].

Although the ACC system is designed to relieve drivers from longitudinal dynamic driving tasks [1] and lower their workload [14], some previous studies [2] have found no statistically significant difference in actual car-following performance (e.g., driver’s response time, time gap, and clearance) between V-ACC and HV. This indicates that assumptions or expectations concerning the ACC system performance might be somewhat ideal. Furthermore, most previous studies mentioned above were conducted on tangent sections or traffic nodes having fixed shapes without considering other road geometric features. However, road curves pose a challenge to the ACC system and its shared control with the human driver, limiting its potential benefits [15]. As shown in Fig. 1, the ACC system fails to detect the leading car and thus transforms to cruise control or disengages to the human driver due to the presence of the road’s curvature and limited field of view (FoV) of V-ACC’s sensors. Note that such a missed detection may propagate as the curve continues and cause a trajectory oscillation, and even sideslip owing to speeding.

![Fig. 1. Challenge to V-ACC’s car-following performance posed by road curves.](image)

In this regard, previous studies focused on developing novel or improved algorithms from a microscopic aspect enabling V-ACC to negotiate the curve and the leading car safely, comfortably, steadily, or eco-friendly [6,16-18]. However, whether such algorithms, which might be still limited in demonstrations for validation, can be applied in commercial V-ACC needs further extensive field tests. To the authors’ best knowledge, very few studies have attempted to investigate the impact of road geometry on V-ACC’s driving performance, which has been highlighted as an essential topic or future work by Makridis et al. [11]. They stated that the empirical data from the Experimental Campaign N.4 of the open-access OpenACC database can lead to significant findings on this topic. He et al. [19] used those data and calibrated the proposed microscopic traffic models, which capture the effects of road slope and curvature on V-ACC’s driving behavior. Nevertheless, limited and indirect geometric data, i.e., only providing trajectory data as an alternative, and fixed and inaccessible ACC system settings due to the proprietary of the manufacturers weaken the generality of those findings.

Given those limitations, Wang et al. [3,4] used high-fidelity virtual simulations to include physics-based sensor models with different technical parameters and dedicated road geometry models with a wide range of geometric features, and then they examined the AV adaptability to the as-built road geometry. However, they only considered the perspective of sight distance safety and ideally assumed that AV could drive on curves without dynamic failures, such as sideslip and rollover. In other words, they focused on the sight distance-related scenario involving AV and the static obstacle but without considering the automation features triggered by interaction with the other surrounding vehicle (e.g., the leading car). Moreover, assessing whether individual vehicle dynamic failure occurs is a vital matter in dealing with coupling effects between vehicles and road geometry [20], particularly concerning V-ACC, which may differ from HV in car-following control sequences. Also, as mentioned above, due to a great deal of investment and anticipation in ACC technology, it is necessary to reconsider V-ACC dynamic and kinematic characteristics on current curves for more driver and passenger-oriented investigations.

Critical curve geometric features might be further extracted if those characteristics approach the margins regarding essential requirements. Given the paradigm of road geometry-vehicle coupling mechanism and features of the ACC system, we focused on the safety, comfort, and speed consistency requirements. In addition, finding such geometric features and their matched V-ACC’s settings or behaviors contributes to improving ACC systems’ operation design domain (ODD), which is recommended by García et al. [21]. Offering such a road-oriented ODD improvement could support road administrators in regulating V-ACC’s behaviors to exert the advantages of ACC technology.

Given those motivations, this study aims to investigate the implications of horizontal curves on V-ACC characteristics. To this end, a virtual co-simulation platform is established to integrate the pros of multiple simulation software. The V-ACC data offered by the OpenACC database are used to validate the established co-simulation platform. Based on that, a series of virtual simulations featuring V-ACC and horizontal curve geometry are conducted to collect the required V-ACC characteristics, followed by interpreting the impact mechanism of geometric features. Finally, critical geometric features subject to the above requirements are extracted by reference to many specified and empirical thresholds for those characteristics. We focused on the current highway geometry instead of urban roads given the widely-used ODD of ACC systems regarding the road type [22] and only considered the vehicle-road interaction.

The study is organized as follows. Section 2 introduces the virtual simulation method and design. Section 3 presents the simulation and analysis results, and Section 4 presents the concluding remarks, limitations, and future work.
II. METHODS

A. Overview

The proposed framework includes four main steps as shown in Fig. 2. First, a virtual co-simulation platform is established by integrating PreScan, CarSim, and MATLAB/Simulink. Second, the coupling simulation of V-ACC and roads executed by the platform is validated with the OpenACC database issued publicly by the Joint Research Centre of the European Commission [23]. Third, numerous test scenarios are designed according to the AV driving scenario generation framework (functional-logical-concrete scenarios) featuring V-ACC (e.g., sensor configuration) and horizontal curves (e.g., circular curve radius). Considering the safety, comfort, and speed consistency requirements, various dynamics and kinematics characteristics (e.g., vertical tire force and acceleration, respectively) of V-ACC are output and derived. Fourth, the impact mechanism of horizontal curves on those characteristics is analyzed followed by extracting critical geometric features subject to the abovementioned requirements.

![Fig. 2. Overview of the proposed framework.](image)

B. Virtual Co-simulation Platform

PreScan® software packages (version 2021.1.0), CarSim (version 2022), and MATLAB/Simulink (version 2021b) were integrated to establish the virtual co-simulation platform. Such a platform does well in physics-based calculations of perception sensors’ operations and is effective in simulating roads, vehicle dynamics and control, ACC systems, and their coupling. In this regard, researchers in the AV domain have extensively employed the platform for optimizing AV control algorithms [24] and developing virtual test technology [25].

![Fig. 3. Co-simulation virtual platform integrated by PreScan, CarSim, and MATLAB/Simulink.](image)

C. Validation

A proportional-integral-derivative (PID) control algorithm widely-used for the commercially deployed ACC system [26,27] is offered and modularized by Simulink, and it is validated, in the PreScan’s built-in demo files, through ten typical ACC real-life scenarios and eight test scenarios specified by ISO test protocols [22]. For example, the leading car drives ahead of V-ACC in the same tangent lane and performs braking and acceleration maneuvers (real-life scenarios); V-ACC follows the leading car on a circular curve at a constant speed, but the leading car decelerates (test scenarios in protocols). However, the validation above only involves the co-simulation between PreScan and Simulink. As a result of the simulation on a coupling of richer geometric features and the integration of CarSim, it is necessary to validate the co-simulation platform further.

As stated by Makridis et al. [11], field tests of the Experimental Campaign N.4 of the OpenACC database, which were conducted on the Handling Course of the ZalaZone ground in Hungary, aim to investigate how road geometry affects V-ACC driving performance. Specifically, the Handling Course with many curves and slopes has a length of 2.2 km and a width of 12 m. The campaign includes ten different kinds of commercial V-ACC (e.g., Tesla, Mercedes-Benz, BMW) as followers and a programmable automated demonstrator vehicle (V-AD) as the leading car, with all speeds regulated to a fixed desired speed irrespective of geometric features. In this regard, the data extracted from this test track was used for validation, and raw data include the vehicles’ position (e.g., local coordinates) and speed (e.g., doppler speed) with precisions of 2 cm and 2 cm/s, respectively, and a constant sampling frequency of 10 Hz.

Besides the geometry information, two widely-used parameters (V-ACC’s speed and clearance) [22,28] were adopted to validate the ACC system function under various geometry conditions within the platform. Therefore, the state of the preceding vehicle is also required as is the case with V-ACC. If the data of any vehicles is missing, this pair of data will be discarded. As a result, the data pair of Toyota (Rav 4,
2019), i.e., V-ACC, and V-AD within the test period of 93-324 s (one lap) was selected and cleaned with a low-pass filter to remove the noise in data analysis software, OriginPro (version 2022). In addition, the ACC system equipped in Toyota adopts a short time gap setting [11]. Many post-processing measurements were acquired based on the raw data, including the driving speed (\( V \)), clearance, curvature, and longitudinal slope (\( i_{\text{g}} \)), as shown in Fig. 4. Note that the curvature and \( i_{\text{g}} \) were calculated based on the V-AD’s path curvature and tangent of the path pitch angle, respectively, which are both consistent with the actual geometry of the test track since V-AD drives along the road centerline [11].

![Fig. 4. Measurements related to vehicles and the test track: (a) path layouts; (b) \( V \) and clearance; and (c) curvature and \( i_{\text{g}} \). Note that curvature and \( i_{\text{g}} \) are positive/negative when turning left/right and upgrades/downgrades, respectively, following the driving direction.](image)

Preliminary results drawn from Fig. 4 are as follows. Those vehicles’ driving paths diverge slightly at curves (Fig. 4(a)). Also, as they approach the curve or/and slope, an increasing maneuvering gap exists between V-ACC and V-AD (Figs. 4(b) and 4(c)), which further confirms the likely impacts of road alignments on ACC system performance and shows their impact features.

Based on the vehicles’ information (e.g., vehicle type) and test measurements (see Fig. 4) stated above, the test scenario was regenerated from the real-life campaign to the co-simulation platform, as shown in Fig. 5. Specific executions in the co-simulation platform related to vehicles and roads are shown in Table 1. Note that \( t_{\text{rec}} \) of V-ACC is calibrated within the range of 1.2-2.2 s because many ACC system configurations (e.g., exact \( t_{\text{rec}} \) value) were not elaborated in the literature. In addition, a constant \( t_{\text{rec}} \) on curves is adopted in the PID-based ACC algorithm to save computing resources and avoid determining the complicated topological relationship between the clearance and road curvature while ensuring the safety and comfort requirements, which is used by many commercial ACC systems [29,30].

![Fig. 5. Test scenario regenerated in the co-simulation platform.](image)

### Table I
**Execution in the co-simulation platform for validation.**

<table>
<thead>
<tr>
<th>Test elements</th>
<th>Execution in the co-simulation platform</th>
</tr>
</thead>
</table>
| **V-AD** | 1. Audi A8 Sedan is adopted.  
2. The trajectory is created by inputting V-AD’s coordinates and \( V \) (see Fig. 4).  
3. The driver model and vehicle dynamics model are not included to allow the vehicle to follow the trajectory above completely. |
| **V-ACC** | 1. BMW X5 SUV is adopted.  
2. The ACC system module and the driver model are adopted for the vehicle’s longitudinal and lateral maneuvers, respectively. The driver model is designed based on optimal preview control theory. Specifically, the ACC system module within the detection ranges of \( d_{i},d_{\text{min}},d_{i}+d_{i}, \) and \( 0-d_{i} \) shall measure the clearance, only detects the presence of the leading car, and is not required to detect its presence, respectively (see Fig. 6), where \( d_{i},d_{i}, \) and \( d_{\text{min}} \) adopt 2 m, 4 m, and sensor’s detection range, respectively [22]. Other parameters (e.g., maximum brake pressure) in the ACC system module and parameters (e.g., preview time) in the driver model are configured using default settings. |
| | 3. For ACC system features, two radio detection and ranging sensors (Radar) are included and configured by default (see Fig. 7) since the exact sensor configuration was neither mentioned by Makridis et al. [11] nor provided by the vehicle manufacturer.  
4. The desired trajectory is created by inputting V-AD’s coordinates and desired speed \( (V_{\text{d}}) \) of 30 km/h (Fig. 4(b)).  
5. The desired time gaps \( (t_{\text{rec}}) \) ranging from 1.2 s to 2.2 s with an interval of 0.1 s are adopted to determine the optimal value [22,22]. This is because the exact \( t_{\text{rec}} \) was neither mentioned by Makridis et al. [11] nor provided by the vehicle manufacturer, and the adopted ACC algorithm and sensor configuration might differ from the real-life campaign. In addition, an adjustable \( t_{\text{rec}} \) on curves is packaged in the ACC system module, which adopts 1.5 times that on the tangent section through real-life data (see Figs. 4(b)-4(c)).  
6. A 27-degree-of-freedom vehicle dynamics model is included. |

### Road
1. The geometry of a one-lane road is rebuilt by using the position data, curvature, and \( i_{\text{g}} \).  
2. Based on the Ministry of Transport of the People’s Republic of China (MTPRC) [31], the cross slope, superelevation, and asphalt pavement friction coefficient (ideal weather) of 2%, 6%, and 0.85, respectively, are adopted corresponding to the average \( F \) of 8 m/s (approximately 30 km/h) for both vehicles (see Fig. 4(b)) since they were not mentioned by Makridis et al. [11].  
3. The pavement surface rotates around the road centerline as the cross slope rises linearly to superelevation.  
4. A lane width of 3.5 m [31] rather than 12 m is adopted for simplifying the simulation.  
5. A tangent section with a length of 20 m is added before the starting point since the results of pre-tests show that the PID-based ACC algorithm requires approximately 2 s to stabilize performance at \( F = 8 \) m/s.  

### Vehicles
States, models (if any), and algorithms (if any) of vehicles are modularized and integrated (Fig. 8 takes V-ACC as an example).
V-ACC  
Fig. 6. Operational domain related to V-ACC detection range (side view).

Sensor model provided by PreScan  
Radar type  
Technology  
Sensor independent  
Detection Hz  
HFoV  
V FoV  
Scan Frequency MHz  
Radar is mounted on the middle of vehicle’s width with a mounting height of 0.6 m.

Sensor model provided by PreScan  
Driver model provided by PreScan  
Vehicle dynamics model provided by CarSim  
V-FoV-based interface & Data extraction provided by PreScan  
Measurement output (e.g., speed, angle, etc.)  
Module of vehicle’s initial state and desired trajectory provided by PreScan, provided by PreScan  
Feedback of vehicle’s steer angle (e.g., yaw, speed, etc.)  
Interface for modularized model integration in CarSim  
Fig. 7. Sensor configuration for ACC system features adopted in the platform, where HFoV and V FoV are horizontal and vertical FoV, respectively.

Also important to note is that current commercial vehicles (e.g., Tesla) equipped with the ACC system also employ other sensors (e.g., camera and laser radar), but we only adopted the sensor configuration of two types of Radar. The reasons are as follows: (i) camera and laser radar are mainly used for other automation features, such as lane marking detection and distant stationary obstacle warning, respectively, while Radar has a priority role in the case of ACC car-following due to its sensitive detection of the leading car’s dynamic state [4]; (ii) we addressed the lacking information regarding the sensor configuration in Makridis et al. [11] by finding the optimal \( \tau_d \) to simulate the explicit ACC performance; and (iii) such a sensor configuration with the technical parameters specified in Fig. 7 has been validated by PreScan in the ISO test for ACC curve capability. In addition, a default and general V FoV of 9 deg was adopted since \( \theta_3 \) is small and thus such a V FoV is sufficient to cover the leading car.

According to those executions, the validation tests at each \( \tau_{de} \) were conducted, followed by comparing the test results with real-life data at each absolute testing timestamp. Note that the testing time in the simulation starts at 0 s, corresponding to the actual starting time of our selected test period of 93 s. The testing period during the pre-stabilized tangent section is not included. The same sampling frequency of 10 Hz is adopted.

A widely-used performance measurement, i.e., root-mean-squared error (RMSE) [32], is used to assess the consistency between simulation results and actual data, as shown in Fig. 9(a). In line with the empirical observations of a short time gap setting, \( \tau_{de} \) of 1.5 s yields the smallest RMSE for both \( V \) (0.6 m/s) and clearance (0.1 m). Figs. 9(b) and 9(c) further show the \( V \) and clearance at \( \tau_{de} = 1.5 \) s, respectively, compared with their ground truth data. Therefore, the fair results at \( \tau_{de} = 1.5 \) s shall be feasible to validate the co-simulation platform.

Fig. 7. Sensor configuration for ACC system features adopted in the platform, where HFoV and V FoV are horizontal and vertical FoV, respectively.

D. Test Scenario Design

According to the scenario design framework defined in the PEGASUS project [33], test scenarios are designed in the following order: functional scenario, logical scenarios, and concrete scenarios.

1) Functional Scenario

Fig. 10 shows the functional scenario, defined as a situation where a V-ACC follows a leading car that drives steadily on a sustained basis along a specific highway alignment in good weather. The road geometry includes tangent sections, spiral transition curves, and a circular curve. The scenario’s objective is to output V-ACC dynamics and kinematics characteristics related to geometric features. It should be noted that the tangent section and spiral transition curve are also considered since generally a circular curve does not exist separately on as-built roads. Also, it is necessary to capture the impacts of curvature variation on those characteristics.

Fig. 9. Simulation results for validation: (a) RMSE for \( V \) of V-ACC and clearance; (b) and (c) are \( V \) and clearance at \( \tau_{de} = 1.5 \) s in simulations versus the actual \( V \) and clearance, respectively.

![Functional scenario](image)

The on-road passenger vehicle type, which is used in MTPRC [31] and aligns with the aforementioned validation setting, is selected for V-ACC and the leading car. The desired driving path of both vehicles is the same. To exclude the impact of surrounding vehicles and focus exclusively on the geometry, a one-lane rightward road is adopted, on which the driving path overlaps the road centerline completely.

Furthermore, specific dynamics and kinematics characteristics of V-ACC, considering safety, comfort, and speed consistency requirements, are as follows:

i) Safety Measures: Two widely-used measurements, coefficient of lateral friction forces (\( \mu \)) [34] and lateral load transfer ratio (\( I_o \)) [35], are adopted as measures of V-ACC sideslip and rollover accidents on curves,
respectively. With the tire forces output by the platform, μ and I_R are estimated by (1) and (2), respectively.

\[
\mu = \frac{F_{yo} + F_{yo}}{F_{zo} + F_{zo}} \quad (1)
\]
\[
I_R = \frac{F_{xo} - F_{xo}}{F_{zo} + F_{zo}} \quad (2)
\]

where, F_{zo} (or F_{yo}) and F_{xo} (or F_{yo}) are the vertical (or lateral) forces of the V-ACC’s tyres near the outer and inner sides of the curve, respectively; F_{yo} (or F_{xo}) is positive and negative when the force vector points towards the outer and inner sides of the curve, respectively.

ii) Comfort Measures: To increase the reliability of comfort results, longitudinal acceleration (A_L) and deceleration (A_D), lateral acceleration (A_y) and its rate (A_{\dot{y}}) are adopted as the primary measures considering much-cited measures for HVs [36] and ACC system functional tests [22]. In addition, μ can also be used to assess comfort [34].

iii) Speed Consistency Measures: As like the concept of ‘automated driving consistency’ introduced by Garcia et al., [37], speed consistency (A_V) is defined as the difference between V and V_{de} in this study to assess how drivers’ expectations and road geometry relate [31].

The critical values of the above characteristics related to (a)-(c) requirements are listed in Table II. Note that V-ACC, which is designed to improve the comfort of drivers and passengers [1,22], only has the additional ACC system and corresponding sensors compared with HV [38] in the matter of vehicle facilities, and thus it is assumed that those critical values for HV also apply to V-ACC.

### TABLE II

**Critical Values of Dynamics and Kinematics Characteristics for Measuring Safety, Comfort, and Speed Consistency.**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Dynamics and kinematics characteristics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>1. Sideslip occurs when</td>
<td>[34,39]</td>
</tr>
<tr>
<td></td>
<td>[</td>
<td>\mu</td>
</tr>
<tr>
<td></td>
<td>2. Rollover occurs when</td>
<td>[35,39]</td>
</tr>
<tr>
<td></td>
<td>[</td>
<td>I_R</td>
</tr>
<tr>
<td>Comfort</td>
<td>1. For the comfort-oriented operational limits of the ACC system, A_L ≤ 2.00 m/s² and A_D ≤ 3.50 m/s² (average over 2 s), A_y ≤ 2.0 m/s².</td>
<td>[22]</td>
</tr>
<tr>
<td></td>
<td>2. Drivers (and passengers) feel:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• <strong>comfortable</strong>: A_L, A_D ≤ 0.1g = 0.98 m/s²; 0 ≤ A_y &lt; 1.8 m/s²; 0 ≤ A_{\dot{y}} &lt; 0.35 m/s²; 0 ≤</td>
<td>[25,31,36,39]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[</td>
</tr>
<tr>
<td></td>
<td>• less comfortable: 0.1g ≤ A_L (or A_D) ≤ 0.2g = 1.96 m/s²; 1.8 m/s² ≤ A_y &lt; 3.6 m/s²; 0.35 m/s² ≤ A_{\dot{y}} &lt; 0.50 m/s²; 0.10 ≤</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[</td>
</tr>
<tr>
<td></td>
<td>• <strong>moderately uncomfortable</strong>: 0.2g ≤ A_L (or A_D) ≤ 0.3g = 2.94 m/s²; 3.6 m/s² ≤ A_y &lt; 5.0 m/s²; 0.50 m/s² ≤ A_{\dot{y}} &lt; 0.60 m/s²; 0.15 ≤</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[</td>
</tr>
<tr>
<td></td>
<td>• <strong>uncomfortable</strong>: A_L (or A_D) ≥ 0.3g; A_y ≥ 5.0 m/s²; A_{\dot{y}} ≥ 0.60 m/s²; [</td>
<td>\mu</td>
</tr>
<tr>
<td>Speed consistency</td>
<td>Speed consistency is good: 0 &lt;</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>poor:</td>
<td>V</td>
</tr>
</tbody>
</table>

### 2) Logical Scenario

a) Vehicles

The same settings for vehicle models, V-ACC’s driver model, and sensor configurations are adopted as in validation (see Table I). Since there is no predefined trajectory, unlike the validation, the default driver model and vehicle dynamics model are included in the leading car. The leading car and V-ACC adopt the same desired path of the road centerline and the same V_{de}. Based on the typical ACC system design domain regarding operational speeds [22,41], a V_{de} range of 40-100 km/h with an interval of 10 km/h is adopted. Except for those desired inputs, the same ACC system module with a constant t_{de} of 1.5 s is adopted for V-ACC.

b) Road Geometry

As shown in Fig. 10, a simple combination of horizontal alignments [42] is adopted without loss of generality. These geometric features are further designed as follows.

The pre-tests revealed that the ACC algorithm needs about 7 s to stabilize performance at V = 100 km/h, resulting in a driving distance of approximately 200 m. Therefore, to ensure geometric design consistency and compliance [31], simplify the simulation, and fully capture the V-ACC’s characteristics at each geometric feature, the lengths of the tangent section (L_1), spiral transition curve (L_3), and circular curve (L_C) are 400 m, 250 m, and 500 m, respectively.

The radius of circular curves (R_C) is determined according to the geometric design specification [31], ACC system design domain [22], and Radar HFoV limitation. Specifically, R_C is compliant with [31], in which values of the design speed (V_d) are assumed to be the same as V_{de} [3], i.e., V_d = 40-100 km/h. In MTPRC [31], R_C shall be larger than the limited minimum radius (R_{min,lim}) or within the range from R_{min,lim} to the common minimum radius (R_{min,com}). Also, ISO [22] specifies a minimum R_c of 125 m for ACC systems in general. As shown in Fig. 11, R_c is further specified by the spatial relationship between vehicles, circular curve, and effective Radar HFoV. Table III lists the minimum feasible R_c free of the Radar HFoV limitation on circular curves. The adopted R_c ranges at each V_{de} are then listed in Table IV.

![Fig. 11. Illustration of the minimum feasible R_c free of the Radar HFoV limitation on circular curves, where θ is the angle between V-ACC’s heading and its sight line aiming toward the leading car; Δd is the sight line distance between V-ACC and the leading car. The derivation of such R_c is presented in the box.](image-url)
TABLE III
MINIMUM FEASIBLE Rc FREE OF THE RADAR HFoV LIMITATION ON CIRCULAR CURVES.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$V_{de}$ (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_c$ (m)</td>
<td>40  50  60  70  80  90  100</td>
</tr>
<tr>
<td>$\Delta d$ (m)</td>
<td>25  30  35  40  45  50  55</td>
</tr>
<tr>
<td>$R_c$ (m)</td>
<td>15  20  25  30  35  40  45</td>
</tr>
</tbody>
</table>

$R_c$ is the minimum feasible $R_c$ for ACC systems is 150 m and the interval is 25 m. $V_{de}$ is the desired speed at which the associated $R_c$ values are rounded to multiples of 25 to simplify the simulation; $\Delta d$ is the desired clearance, as stated above. At $V_{de} = 40$ km/h, $\Delta d = 25$ m > 30 m and thus $R_c \geq 2$ tan(4.5 deg) / $\Delta d$. $R_c$ is the minimum feasible $R_c$ for ACC systems is 150 m and the interval is 25 m. $V_{de}$ is the desired speed at which the associated $R_c$ values are rounded to multiples of 25 to simplify the simulation; $\Delta d$ is the desired clearance, as stated above. At $V_{de} = 40$ km/h, $\Delta d = 25$ m > 30 m and thus $R_c \geq 2$ tan(4.5 deg).

TABLE IV
ADOPTED $R_c$ RANGES$^1$.

<table>
<thead>
<tr>
<th>$R_c$ (m)</th>
<th>$V_{de}$ (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{min}$, $R_{max}$</td>
<td>40  50  60  70  80  90  100</td>
</tr>
<tr>
<td>$R_{min}$, $R_{max}$</td>
<td>60  100  125  200  250  325  400</td>
</tr>
<tr>
<td>$R_{min}$, $R_{max}$</td>
<td>0  150  200  300  400  550  700</td>
</tr>
</tbody>
</table>

$^1$Adopted $R_c$ range and adopted $R_c$ values are rounded to multiples of 25 to simplify the simulation; $^2$At $V_{de} = 40-90$ km/h, the associated $R_{min}$, $R_{max}$ are not all greater than the other two minimum $R_c$ considerations, and thus the adopted $R_c$ ranges at $V_{de} = 40-70$ km/h are somewhat increased to ensure sufficient test ranges and output data, while at $V_{de} = 80$ and 90 km/h the upper bound remains the same and the lower bound increases.

c) Concrete Scenarios

Concrete scenarios (sum of (adopted $R_c$ range) / interval + 1) = 4 + 4 + 4 + 7 + 8 + 13 = 41) are designed through the pairs sampling approach [43], which involves all feature combinations within the defined range in the logical scenario.

E. Test Procedure

The test procedure for each trial, as shown in Fig. 12, involves the following steps.

1. Let V-ACC follow the leading car along the desired path at $V_{de}$ from their respective preset starting to end positions.

2. Collect V-ACC’s dynamics and kinematics characteristics related to geometric features.

3. Ensure that the ACC system is activated.

4. Follow the leading car along the desired path at $V_{de}$ from their respective preset starting positions to end positions.

5. The initial speed of V-ACC is set to 2 km/h larger than $V_{de}$ to ensure the ACC system is activated. Otherwise, V-ACC may follow at $V_{de}$ constantly without activating the ACC system. The initial clearance is further adjusted to be shorter than the desired clearance, i.e., $(t_{de} \times V_{de}) / 3.6$ m, by (0.1 s x initial speed / 3.6 m). Table V lists the adjusted initial speed of V-ACC and initial clearance.

III. RESULTS AND DISCUSSION

Figs. 13-18 depict variations of $\mu$, $I_R$, $A_x$, $\Delta x_y$, $A_x$ (or $A_\alpha$), and $V$ along $S_d$, respectively. Note that $S_d$ is divided into the following sections: 0-400 m, 400-650 m, 650-1150 m, 1150-1400 m, and 1400-1800 m to denote sections of the entry tangent (T1), entry spiral (S1), circular curve (C1), exit spiral (S2), and exit tangent (T2), respectively, within the adopted simple combination of horizontal alignments.
Fig. 13. \( \mu \) of V-ACC along \( S_a \): (a)-(g) are \( V_{de} = 40-100 \) km/h, respectively.

Fig. 14. \( I_R \) of V-ACC along \( S_a \): (a)-(g) are \( V_{de} = 40-100 \) km/h, respectively.

Fig. 15. \( A_y \) of V-ACC along \( S_a \): (a)-(g) are \( V_{de} = 40-100 \) km/h, respectively.
As shown in Figs. 13-18, all characteristics’ fluctuating amplitude and frequency are generally the largest and slowest, respectively, in C1, followed by S1/S2 and T1/T2. Also, their variation curves along $S_o$ are approximately axisymmetric or central symmetric toward the characteristic-axis or $S_o$-axis point, respectively, in the middle length of C1 ($S_o = 900$ m), which aligns with the anticipation caused by the symmetrical distribution of geometric features. However, some variation curves present a right-skewed distribution within C1, indicating that such characteristics vary asymmetrically in the corresponding $V_{de}$ and $R_C$ conditions as V-ACC leaves S1 and enters S2. For example, $V$ increases faster within C1-S2 than it decreases within S1-C1 (see Fig. 18(f)). In addition, a smaller $R_C$ causes all characteristics towards the margins of safety, comfort, or speed consistency.
The above characteristics are coupled with and provide feedback to V-ACC’s $V$ since $V$ is the most explicit measurement during V-ACC’s driving. They are derivative effects of V-ACC’s driving state variations caused by the ACC system features. Therefore, to understand the variation features of other characteristics, V-ACC’s primary maneuver and $V$ variations along consecutive geometric features (i.e., T1-T2 sections) are shown in Fig. 19 and clarified as follows. Note that hysteresis effects [44] on the vehicle dynamics model (e.g., suspension and brake) are included in simulations; $\theta$ and $\Delta d$ refer to Fig. 11. Moreover, V-ACC’s maneuver considers two primary actuators, i.e., throttle and brake, executing sustained longitudinal V-ACC’s motion control. The platform also outputs their results, although this study does not present their variations along $S_a$.

![Fig. 19. Simplified illustration of V-ACC’s primary maneuver and $V$ variations along consecutive geometric features. Note that ‘(x, y)’ denotes V-ACC and the leading car driving on the ‘x’ and ‘y’ geometric feature sections, respectively.

(i) (T1, T1) and (T1, S1): Since both curvatures of T1 and S1’s front ends are small, $\theta$ is small and thus $\Delta d$ (also referred to as the detected clearance) is the same as the desired clearance. The throttle holds open to sustain $V_{de}$.

(ii) (S1, S1): Since S1’s rear end near C1, $\theta$ increases and thus $\Delta d$ is increasingly shorter than the desired clearance. Consequently, the throttle is closed and $V$ is then reduced by braking.

(iii) (S1, C1): Due to the C1 curvature, the maneuver follows the previous braking and $V$ continues to decline. Also, $V$’s fluctuating amplitude tends to amplify.

(iv) (C1, C1): Since $v_{de}$ increases to 1.5$v_{de}$ as V-ACC enters C1, the maneuver continues to brake, and the cumulative decrease in $V$ during (b)-(c) is adequate. The maneuver further turns to opening the throttle, increasing $V$ with a smaller fluctuating amplitude, and maintaining the clearance.

(v) (C1, S2), (S2, S2), (S2, T2), and (T2, T2): Contrary to (a)-(d), $\theta$ and $\Delta d$ are decreasing and increasing, respectively, and 1.5$v_{de}$ decreases to $v_{de}$. Therefore, the maneuver follows the previous opening of the throttle and then holds it.

As stated above, asymmetrical maneuvers of V-ACC exist between S1-C1 and C1-S2. Such maneuvers result from the characteristics’ variations presented in the previous driving process, and they are also the cause of those in the following process. Interestingly, the same asymmetrical maneuver is found in the car-following scenario only involving HVs, as measured by the driving path and speed [45,46]. This is attributed to the fact that human drivers would negotiate the curved road, including spiral and circular curves, by visual perception, psychology, driving experience, and skills instead of completely following the lane centerline and performing symmetrical speed control.

It should be noted that a considerable $V$ fluctuation occurs along with other characteristics’ large fluctuations under some $V_{de}$ conditions with a small specified $R_c$, resulting in their corresponding maneuvers non-compliant with the general manner stated above. Because many commercial ACC systems are likely to remain as black boxes [10] and consideration for curve geometry is missed, the specific impact mechanism underlying this result has not been disclosed in previous studies. Easa et al. [47] stated that V-ACC employs a technical structure of parallel dual-driving and dual-control, i.e., shared control, where both the human driver and ACC system have independent driving ability and participate in the driving maneuver. The human driver and ACC system are characterized by the driver model and ACC system module used for V-ACC in the present study. Therefore, the mechanism is interpreted as follows.

In T1/T2, the ACC system module can handle V-ACC’s longitudinal maneuver steadily since the driver model only needs to maintain zero steering output. However, in S1/S2 or C1, the curvature ahead and dynamic state of the leading car are fed into the ACC system module continuously and the driving trajectory is then adjusted jointly from longitudinal and lateral directions by the module and model, respectively, to satisfy $V_{de}$. Throughout this process, the delay of the driver’s preview in updating curvature and the instantaneous adjustment of lateral motion control affect the system’s detection and longitudinal motion control, yielding closed-loop feedback and characteristics’ fluctuation. The driver negotiates not only the curve but also the ACC system. Therefore, such negotiation becomes increasingly challenging and unstable as the curvature increases.

To extract critical geometric features subject to the safety, comfort, and speed consistency requirements, and to use the results shown in Figs. 13-18 into practical applications, e.g., defining the road-oriented ODD, those results were further compared with their critical values listed in Table II. Specifically, given that most results satisfy their corresponding requirement through figure reading, only the maximum values of $|\mu|$, $|v|$, $A_y$, $A_{ax}$, $A_{sd}$, and $|V - V_{de}|$ ($\mu_{max}$, $v_{max}$, $A_{y_{max}}$, $A_{ax_{max}}$, $A_{sd_{max}}$, and $V_{max}$, respectively) along $S_a$ and their occurrence sections ($S_{type}$-
S1, C1, S2, and T2) were captured first and the critical geometric features with \( V_{dc} \) were then obtained by comparing those characteristics’ maximum values with their critical values, as shown in Table VI. Note that all characteristics are likely to develop steadily in T1 in real-life scenarios since \( V_{dc} \) and \( f_{dc} \) are easy to follow. Consequently, the fluctuating interferences caused by the user-defined initial speed and clearance (Table V) are excluded, and only the maximum values within the sections after T1 were captured.

### Table VI

**Maximum values of dynamics and kinematics characteristics along \( S_a \), their occurrence sections, and critical geometric features with \( V_{dc} \).**

<table>
<thead>
<tr>
<th>( V_{dc} ) (km/h)</th>
<th>( R_c ) (m)</th>
<th>( \mu_{\text{max}} )</th>
<th>( y_{\text{R max}} )</th>
<th>( \Delta y_{\text{max}} )</th>
<th>( y_{\text{type}} )</th>
<th>( \Delta y_{\text{max}} )</th>
<th>( x_{\text{max}} )</th>
<th>( y_{\text{max}} )</th>
<th>( T_\text{max} )</th>
<th>( \Delta V )</th>
<th>( S_{\Omega max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>125</td>
<td>0.02</td>
<td>0.02</td>
<td>1.0</td>
<td>0.20</td>
<td>0.03</td>
<td>S1</td>
<td>0.07</td>
<td>S2</td>
<td>2</td>
<td>T2</td>
</tr>
<tr>
<td>50</td>
<td>225</td>
<td>0.06</td>
<td>0.05</td>
<td>1.6</td>
<td>0.31</td>
<td>C1</td>
<td>1.81</td>
<td>T2</td>
<td>2.26</td>
<td>T2</td>
<td>7</td>
</tr>
<tr>
<td>60</td>
<td>300</td>
<td>0.12</td>
<td>0.10</td>
<td>2.0</td>
<td>0.56</td>
<td>C1</td>
<td>0.84</td>
<td>T2</td>
<td>0.44</td>
<td>T2</td>
<td>4</td>
</tr>
<tr>
<td>70</td>
<td>325</td>
<td>0.08</td>
<td>0.06</td>
<td>1.7</td>
<td>0.36</td>
<td>S1</td>
<td>0.56</td>
<td>C1</td>
<td>0.17</td>
<td>S1</td>
<td>4</td>
</tr>
<tr>
<td>80</td>
<td>350</td>
<td>0.06</td>
<td>0.05</td>
<td>1.5</td>
<td>0.35</td>
<td>C1</td>
<td>0.64</td>
<td>S1</td>
<td>0.20</td>
<td>S1</td>
<td>5</td>
</tr>
<tr>
<td>90</td>
<td>375</td>
<td>0.07</td>
<td>0.07</td>
<td>1.7</td>
<td>0.45</td>
<td>S2</td>
<td>0.68</td>
<td>C1</td>
<td>0.22</td>
<td>C1</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>400</td>
<td>0.11</td>
<td>0.09</td>
<td>1.9</td>
<td>0.44</td>
<td>C1</td>
<td>0.76</td>
<td>C1</td>
<td>0.31</td>
<td>S1</td>
<td>6</td>
</tr>
<tr>
<td>425</td>
<td>0.10</td>
<td>0.10</td>
<td>0.18</td>
<td>1.8</td>
<td>0.44</td>
<td>S1</td>
<td>0.53</td>
<td>C1</td>
<td>0.31</td>
<td>S1</td>
<td>6</td>
</tr>
<tr>
<td>450</td>
<td>0.08</td>
<td>0.07</td>
<td>1.7</td>
<td>0.42</td>
<td>S1</td>
<td>0.97</td>
<td>C1</td>
<td>0.31</td>
<td>C1</td>
<td>6</td>
<td>C1</td>
</tr>
<tr>
<td>475</td>
<td>0.08</td>
<td>0.07</td>
<td>1.6</td>
<td>0.44</td>
<td>S2</td>
<td>0.61</td>
<td>C1</td>
<td>0.30</td>
<td>C1</td>
<td>6</td>
<td>C1</td>
</tr>
<tr>
<td>500</td>
<td>0.07</td>
<td>0.06</td>
<td>1.6</td>
<td>0.40</td>
<td>S1</td>
<td>0.67</td>
<td>C1</td>
<td>0.31</td>
<td>C1</td>
<td>5</td>
<td>C1</td>
</tr>
<tr>
<td>525</td>
<td>0.06</td>
<td>0.06</td>
<td>1.5</td>
<td>0.44</td>
<td>S2</td>
<td>0.47</td>
<td>C1</td>
<td>0.31</td>
<td>S1</td>
<td>6</td>
<td>C1</td>
</tr>
<tr>
<td>550</td>
<td>0.06</td>
<td>0.05</td>
<td>1.4</td>
<td>0.41</td>
<td>C1</td>
<td>0.62</td>
<td>C1</td>
<td>0.30</td>
<td>C1</td>
<td>5</td>
<td>C1</td>
</tr>
<tr>
<td>575</td>
<td>0.04</td>
<td>0.05</td>
<td>1.3</td>
<td>0.42</td>
<td>S2</td>
<td>0.43</td>
<td>C1</td>
<td>0.22</td>
<td>C1</td>
<td>5</td>
<td>C1</td>
</tr>
<tr>
<td>600</td>
<td>0.04</td>
<td>0.05</td>
<td>1.3</td>
<td>0.42</td>
<td>S2</td>
<td>0.59</td>
<td>C1</td>
<td>0.24</td>
<td>C1</td>
<td>4</td>
<td>C1</td>
</tr>
<tr>
<td>625</td>
<td>0.03</td>
<td>0.03</td>
<td>1.3</td>
<td>0.40</td>
<td>S2</td>
<td>0.48</td>
<td>C1</td>
<td>0.30</td>
<td>C1</td>
<td>4</td>
<td>C1</td>
</tr>
<tr>
<td>650</td>
<td>0.03</td>
<td>0.05</td>
<td>1.2</td>
<td>0.41</td>
<td>S2</td>
<td>0.75</td>
<td>C1</td>
<td>0.31</td>
<td>C1</td>
<td>5</td>
<td>C1</td>
</tr>
<tr>
<td>675</td>
<td>0.02</td>
<td>0.05</td>
<td>1.2</td>
<td>0.38</td>
<td>S2</td>
<td>0.64</td>
<td>C1</td>
<td>0.30</td>
<td>C1</td>
<td>5</td>
<td>C1</td>
</tr>
<tr>
<td>700</td>
<td>0.02</td>
<td>0.05</td>
<td>1.1</td>
<td>0.38</td>
<td>S2</td>
<td>0.75</td>
<td>C1</td>
<td>0.31</td>
<td>C1</td>
<td>5</td>
<td>C1</td>
</tr>
</tbody>
</table>

Note:  
- \( \mu_{\text{max}} \): comfortable: [0, 0.10] \hspace{1cm} less comfortable: [0.10, 0.15] \hspace{1cm} moderately uncomfortable: [0.15, 0.20]  
- \( y_{\text{R max}} \): no rollover occurs: [0, 0.5]  
- \( \Delta y_{\text{max}} \) (m/s²): less comfortable and smaller than the system limit: [0.8, 2.0] \hspace{1cm} less comfortable and larger than the system limit: [2.0, +∞]  
- \( y_{\text{type}} \): comfortable: [0.35, 0.50] \hspace{1cm} moderately uncomfortable: [0.50, 0.60] \hspace{1cm} uncomfortable: [0.60, +∞]  
- \( \Delta V \) (km/h): good: \( 0 \leq \Delta V < 10 \) \hspace{1cm} moderately uncomfortable: [1.96, 2.94]  
- \( S_{\Omega max} \):  

As shown in Table VI, given the same \( R_c \), all characteristics’ maximum values increase as \( V_{dc} \) increases, but neither sideslip nor rollover occurs since \( \mu_{\text{max}} \leq 0.30 \) and \( y_{\text{R max}} \leq 0.5 \), respectively. Also, speed consistency is good as \( \Delta V_{\text{max}} \leq 10 \) km/h. In such a case, it is not surprising to see that V-ACC ensures its safety without a sideslip or rollover since we adopted a default driver model, which simulates the lateral maneuvers of a driver who is always in the control loop and not distracted. However, V-ACC’s drivers might be out of the loop or have lower situation awareness due to a mismatch between their...
expectations of V-ACC capabilities and its actual capabilities as prescribed in the original equipment manufacturer’s manual [48]. Critical values of \( \Delta y \) and \( A_{sa} \) (or \( A_{sd} \)) regarding comfort measurements present the most rigorous and moderate requirements, respectively, whereas the other characteristics are the same. According to \( \Delta y \)’s critical values, for the V-ACC’s driver and passenger (if any), most geometric conditions at \( V_{de} = 40-100 \text{ km/h} \) are ‘less comfortable’ toward ‘moderately uncomfortable’ or even ‘uncomfortable’.

Specifically, the comfort levels measured by \( \mu_{max}, A_{y_{max}}, \) and \( \Delta y_{max} \) in \( R_C = 250-300 \text{ m} \) at \( V_{de} = 60 \text{ km/h} \), \( R_C = 300 \text{ m} \) at \( V_{de} = 70 \text{ km/h} \), and \( R_C = 400, 425 \text{ m} \) at \( V_{de} = 100 \text{ km/h} \) are less comfortable or uncomfortable, which are worse than those in other \( R_C \) and \( V_{de} \) conditions. Note that a ‘less comfortable’ or ‘moderately uncomfortable’ \( A_{sa_{max}} \) (or \( A_{sd_{max}} \)) is found in \( R_C = 225 \text{ m} \) at \( V_{de} = 50 \text{ km/h} \), whereas other characteristics are ‘comfortable’. Regarding those geometric conditions, a smaller \( R_C \) causes the comfort level to be ‘less comfortable’, which is against the ACC system’s primary design objective. Furthermore, the maximum value might be captured earlier within S1 (e.g., \( l_{R_{max}} \)), later until S2 (e.g., \( \Delta y_{max} \)), or even in T2 (e.g., \( A_{sa_{max}} \) or \( \Delta V_{max} \)), instead of within C1 necessarily. This indicates that, given the as-built curved road with a constant \( R_C \), it needs to recommend deaccelerating \( V_{de} \) before S1 and throughout C1, S2, and T2, which can be achieved by placing ACC system-dependent deceleration signs on the roadside, adjusting the system’s \( V_{de} \) design/setting automatically, or alerting the human driver proactively to take over (Fig. 20).

We took ‘moderately uncomfortable’ as the bottom line and concluded the feasible results from Table VI. V-ACC can follow the leading car comfortably on horizontal curves with compliant \( R_C \) at \( V_{de} = 40, 80-100 \text{ km/h} \); however, the driver and passengers (if any) of V-ACC at \( V_{de} = 50-70 \text{ km/h} \) will feel uncomfortable on horizontal curves with a \( R_C \) toward its adopted range’s lower limit. Similar to \( V_{de} = 80-100 \text{ km/h} \) having the high-type geometric features (e.g., large \( R_C \)), it is also noticed that no critical geometric features at \( V_{de} = 40 \text{ km/h} \) are extracted. It might be attributed to the fact that the short-range Radar can still ensure V-ACC’s following function here, but it is not feasible if \( V_{de} \) increases to 50-70 km/h while \( R_C \) remains small. Furthermore, according to these results, it is recommended to improve the ACC system’s ODD from the road geometry perspective and implement the necessary measures mentioned above to reduce \( V_{de} \), thereby adapting V-ACC to the as-built curve roads.

**IV. CONCLUDING REMARKS**

This study has analyzed V-ACC dynamic and kinematic characteristics on as-built highway horizontal curves using a co-simulation approach to provide valuable insights into the impact mechanism of curve geometric features, and the adaptability of the ACC system from the perspectives of safety, comfort, and speed consistency. Also, critical curve geometric features are extracted to help road administrators regulate V-ACC behaviors and improve road-oriented ODD. Based on the present study, the following comments are offered:

- The virtual co-simulation platform was established by integrating PreScan, CarSim, and MATLAB/Simulink and was validated by the OpenACC database. According to the AV-dedicated scenario generation framework, 7 types of dynamic and kinematic characteristics (\( \mu, I_R, A_{y}, \Delta y, A_{sa}, A_{sd}, \) and \( V \)) were output, and 41 concrete scenarios featuring \( V_{de} \), desired clearance (or \( \tau_{de} \)), and \( R_C \) were created. To the authors’ best knowledge, this study is the first attempt to reconsider the current V-ACC’s adaptability on as-built highway horizontal curves and determine the corresponding critical geometric features.

- The validation yielded fair results, indicating that the virtual co-simulation platform can serve as a sound tool and supplement for expanding the data of Experimental Campaign N.4 of the OpenACC database. Also, it can be conveniently further improved by adjusting the parameters of the ACC system module and applying it to extensive tests involving more complicated geometry (e.g., combined alignments). Besides, the test scenario designed for interactions among the leading car, V-ACC, and road geometry based on the specified framework (functional-logical-concrete scenarios) provides a design reference for related studies.

- Given the same desired speed (or design speed), a smaller circular curve radius causes all selected characteristics toward the margins of safety, comfort, speed consistency, and the limit of Radar’s HFOV. Also, a sizeable fluctuating amplitude was observed on circular curves. The human driver negotiates not only the curve but also the ACC system, mainly due to
the technical structure of shared control employed by V-ACC, and thus asymmetrical maneuvers were observed before and after the circular curve, which is in line with HV’s behavior.

- In the simulation, neither sideslip nor rollover occurs, and speed consistency is good. Classified by the critical $\Delta_v$ values, the most rigorous comfort outcomes are as follows: most $R_c$ conditions at $V_{dc} = 40$-100 km/h for V-ACC are ‘less comfortable’ toward ‘moderately uncomfortable’ or even ‘uncomfortable’. With the circular curve radius meeting the current specifications, it is comfortable for the driver and passengers (if any) of V-ACC at $V_{dc} = 40$ km/h, 80-100 km/h following the leading car on horizontal curves. However, when the radius decreases toward its lower limit, they will feel ‘moderately uncomfortable’ at $V_{dc} = 50$-70 km/h. Also, this discomfort might exist before and after the circular curve. To address these issues, some feasible measures were recommended to lower the desired speed. Otherwise, the results can be used directly to improve the road-oriented ODD of ACC systems.

- The study’s main limitation is that it did not consider vertical and combined alignments. Since these alignments are likely to affect V-ACC’s longitudinal dynamics, more tests are expected to uncover more issues regarding adaptability. Furthermore, many constant desired speeds equal to the design speeds along the entire alignment were used in the simulation, which can be adjusted based on feasible naturalistic or empirical data in future research. Also, it would be interesting to check distracted V-ACC drivers through driving simulations or their driver model. In addition, we plan to investigate more automation features, such as the ACC system combined with the lane-keeping assist system (Level 2), and conduct simulations on adverse weather, such as rainy days.

REFERENCES


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